# Subgrid Scale Modeling For LES Simulation of Flow In A Turbulent Bottom Boundary Layer

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## LONG-TERM GOAL

The long-range goal of this work is to develop improved understanding and predictive capability for shallow water dynamics.

## OBJECTIVE

To develop a subgrid scale model for large eddy simulation (LES) of the flow in a turbulent stratified flow in shallow water, based on parameterizations determined from field measurements, direct numerical simulation (DNS) studies, and theoretical considerations. The aim is to provide accurate characterization of energy dissipation and Reynolds stress close to surface and bottom boundaries in a way which can be easily incorporated in predictive, coarse-grid models of flow in the littoral zone under a variety of conditions. This work is complementary to other ongoing ONR funded computational (Slinn) and observational (Dhanak) studies.

## APPROACH

The work involves theoretical analysis, numerical computations, and comparison with field measurements. The primary research tools are three-dimensional DNS and LES models, which allow simulation of ocean dynamics in shallow water and surface boundary layers.

## WORK COMPLETED

*1)* Large-eddy simulations of turbulent penetrative convection in shallow water caused by the passage of a cold air front have been completed. A paper "Turbulent convection driven by surface cooling in shallow water" by Zikanov, Slinn & Dhanak has been published: *Journal of Fluid Mechanics, 2002, vol. 464, 81-111.*

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*2)* The LES numerical model used in the first part of the project has been modified to include the effects of the Earth's rotation and wind stress at the water surface. The model has been applied to simulations of the turbulent Ekman layer near the ocean surface. Full-scale simulations of the neutrally stratified Ekman layer at different latitude have been carried out and analyzed. The results are reported in a paper entitled "Large-eddy simulations of the wind-induced turbulent Ekman layer" by Zikanov, Slinn and Dhanak has been submitted to *Journal of Fluid Mechanics*.

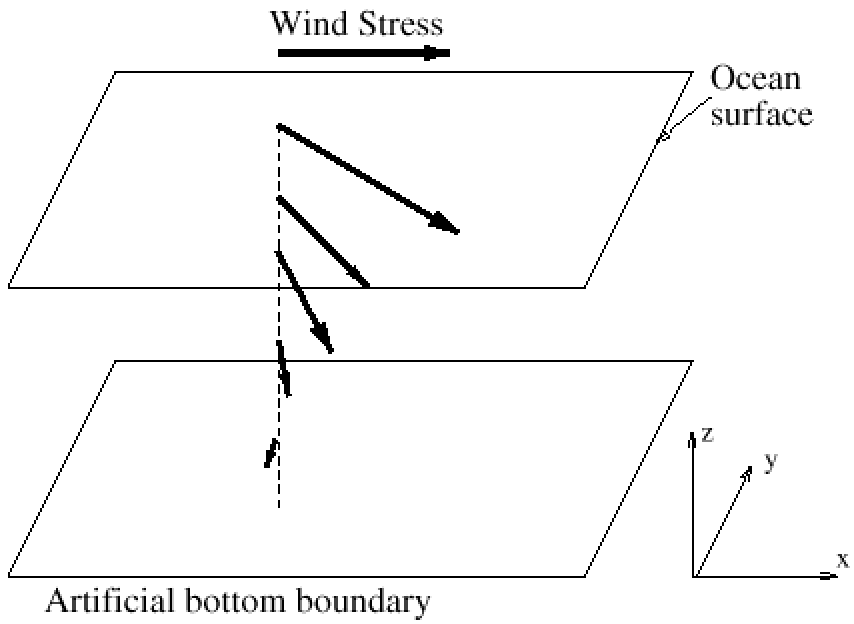


***Figure 1. Schematics of the model problem***

**RESULTS**

Detailed results of the investigation of the turbulent Ekman layer (Figure 1) generated by a steady wind stress applied at the water surface are reported in a paper submitted to Journal of Fluid Mechanics (see below). The traditional formulation of the problem in the absence of the effects of stratification, surface convection, and gravity waves was considered. In an extensive series of LES numerical experiments, we showed that even in this case the classical Ekman model does not adequately describe the mean induced current distribution. The main cause for this appears to be the inadequacy in Ekman's model of a constant effective viscosity coefficient $A_z$ and of a flow that is not affected by the tangential component of the Earth rotation vector ('*f*-plane' approximation). Our simulations have shown that neither of these assumptions is justified.

We found that the effective viscosity concept by itself is relevant for the mean flow but the viscosity $A_z$ varies strongly across the layer. It grows with depth in a subsurface layer of about ¼ the turbulent length $u_*/f$, reaches the maximum value of about $0.025u_*^2/f$ and subsequently decreases with depth (see Figure 3d below). The simulations showed that the effective viscosity variability results in a mean flow profile that deviates significantly from the Ekman spiral. For example, the angle between the surface current and the wind was found to be $28.5^0$, which is in clear disagreement with Ekman's value of $45^0$.

A particularly strong difference was detected in the rate of decay of the computed current amplitude with depth, it being much higher than that predicted by the Ekman model.

An approximate solution, involving Bessel functions, has been obtained as an improvement to the original Ekman model (see Figure 2 below). The solution is based on approximating the vertical distribution of the effective viscosity by a piecewise-linear function (Figure 3d).

Numerical experiments performed at different latitude $\lambda$ and wind angle $\gamma$ revealed that the flow is strongly affected by the Coriolis force associated with the tangential component of the Earth rotation vector (see Figure 4 below). Both the mean current and turbulent fluctuations were found to depend on $\lambda$ and $\gamma$. Perhaps, the most interesting aspect for oceanographic applications is that, except for the latitude of $90^0$, the maximum (minimum) vertical turbulent momentum transfer occurs with North-East (South-West) winds.

Our analysis confirmed the validity of the underlying physical mechanism proposed earlier by other authors, in particular by Tritton (1978). The two main constituents of the mechanism are the redistribution of the turbulent kinetic energy between the vertical and horizontal velocity fluctuations and the modification of vertical turbulent momentum transfer.

Some of the numerical results of the simulations are illustrated in the figures below.

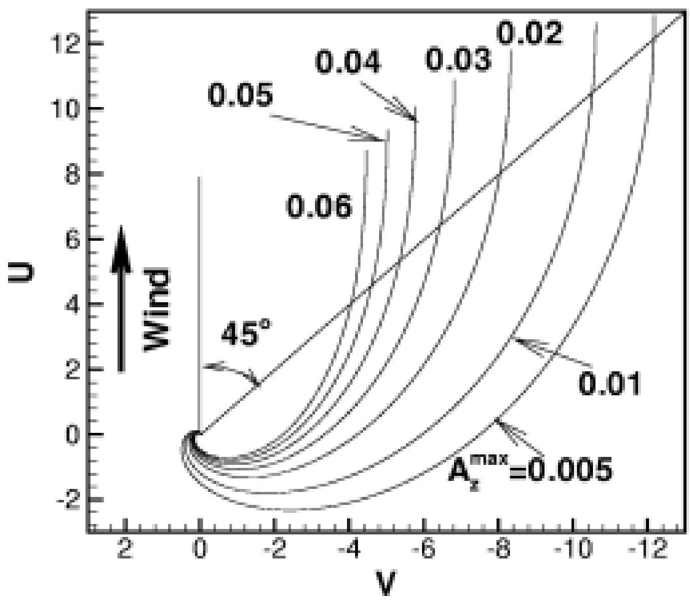


***Figure 2. Velocity hodographs of Bessel function solutions for*** $z_{\max} = L_z - 0.222$ ***and various values of*** $A_z^{\max}$

***Figure 3. Horizontally and time-averaged profiles calculated in the developed turbulent flow for $\lambda = 90^0$. (a) x-z components of sub-grid scale and Reynolds stresses; (b) y-z components of sub-grid scale and Reynolds stresses; (c) Angles between the wind direction and the direction of the total stress vector $\beta_1$, mean shear vector $\beta_2$, and the shear vector in the Ekman solution $\beta_E$; (d) ------, Effective viscosity coefficient evaluated using the computed stress and shear profiles, –••–••–••–linear dependence $A_z = \kappa(L_z - z)$ used by Madsen (1977);••••••••, constant viscosity coefficient $A_{zE} = 0.0144$ of the Ekman model, - - - - -, Piecewise-linear approximation of the viscosity profile used for an approximate solution; (e) Amplitude of the mean current vs. logarithm of depth; (f) Mixing length.***

***Figure 4. Impact of latitude $\lambda$ and the wind angle $\gamma$ on the mean velocity profile (a)-(c) Velocity hodographs; (d) Surface angle $\alpha(L_z)$ between the current and the wind direction as a function of $\gamma$ at different $\lambda$, (e) Speed of the surface current $S(L_z)$, (f) Depth of exponential decay of the current D.***

## IMPACT/APPLICATIONS

An important potential benefit of our work for the ocean community is that it serves to develop and validate an accurate and efficient LES model for oceanic turbulence. Furthermore, our work

contributes to better understanding of fundamental properties of such an important phenomenon as the turbulent Ekman layer near the ocean surface.

## TRANSITIONS

The LES code that has been developed will allow us to consider several types of problems, such as developing mixed layers in response to unsteady wind fields, combined influences of shear and wind effects and other factors of importance in flows in the littoral zone.

## RELATED PROJECTS

The work is carried out in conjunction with field measurements under grant N00014-96-1-5023.

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## PUBLICATIONS


Zikanov, O., Slinn, D. N., & Dhanak, M. R. 2002 "Turbulent convection driven by surface cooling in shallow water," *Journal of Fluid Mechanics, vol. 464, pp. 81-111.*
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Zikanov, O., Slinn, D. N., & Dhanak, M. R. 2002 "Large-eddy simulations of the wind-induced turbulent Ekman layer" submitted to *Journal of Fluid Mechanics*.
(http://www.oe.fau.edu/~manhar/ekman2.pdf)